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EFFECT OF CYCLOTRON IRRADIATION ON CREEP OF ALUMINUM

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ABSTRACT

A suppression of the creep rate in 99.99 per cent pure aluminum wire due to the effects of irradiation by a 38-Mev alpha particle beam has been found. A comparison was made in 27 cases, of the creep rate with beam to the creep rate without beam for the same specimen at neighboring time intervals and at the same temperature. In each case there was a suppression of the creep rate which amounted to a factor of two in some instances, or as much as a factor of eight, depending on the evaluation of experimental errors. Evidence is given to show that this effect is probably not due to temperature changes.

This report is based upon studies conducted for the Atomic Energy Commission under Contract AT-11-1-GEN-8.

ACKNOWLEDGMENT

The cyclotron bombardments were performed by the NAA Berkeley Operations Group with the cooperation of the Crocker Laboratory staff. It is a pleasure to acknowledge the interest and cooperation of Professor Joseph G. Hamilton, Director of Crocker Laboratory.

This and similar work involving the cyclotron is made possible by Professor E. O. Lawrence, who has courteously made available the facilities of the University of California Radiation Laboratory.

I. INTRODUCTION

One of the important problems in reactor technology is the possible effect of irradiation on creep. It has been though that irradiation would influence the creep rate,[1,2] and some experimental substantiation has been given by a paper by Andrade[3] describing experiments in which cadmium single crystals were irradiated by Po alpha particles. He found that the creep rate was increased several times by the bombardment. A similar experiment with aluminum was performed, giving null results, by J. H. Kittel[4] of the NACA. Actually, Andrade was studying the effect of conditions at the surface of a metal on the creep rate. The present paper is a preliminary report on experiments with aluminum, using alpha particles of very much higher energy ($\sim$38 Mev) than those available from polonium, and which penetrate the entire specimen. The purpose of the experiments is to obtain information from which the plastic properties of aluminum in high flux reactors may be predicted.

The method of simulating reactor irradiation in the cyclotron has been discussed from the experimental and theoretical points of view and measurements have been made of the equivalence of cyclotron particles and reactor irradiation for some phenomena.[5,6,7] There are certain advantages in studying radiation damage in the cyclotron beam rather than in reactors. There is ample space about the cyclotron target and there is no nuclear heating or irradiation effect on the equipment generally. The problem of radioactivity is very much reduced so that in the worst cases, the targets may be inspected after a few days "cooling off". It is very easy to check the equipment during an experiment. At the same time an intensity of irradiation comparable or greater than that to be obtained in MTR may be achieved. The principal disadvantage, at least with respect to neutron irradiation, is the requirement for extremely rapid temperature control, imposed by the fact that the beam heat power is subject to sudden fluctuations which will produce a significant temperature deviation in the specimen unless the temperature control system has an extremely rapid response.

II. METHOD OF THE EXPERIMENT

The creep specimen is mounted in apparatus shown diagramatically in Fig. 1, and in the photograph Fig. 2. This apparatus is mounted on a support which is bolted firmly to the cyclotron vacuum tank. A screw adjustment is provided for fine vertical positioning of the creep wire. The beam (39 Mev) passes through one dural window (8.29 mg/cm^2) and through a collimating slot located at the specimen target box. It then passes through the slots in the heater to the specimen and finally ends in a beam stopper. The apparatus is seen in the direction of the beam, in Figs. 1 and 2. An iron constantan couple, which is shown in Fig. 1, resistance welded to the specimen, provides a measurement of the specimen temperature and a means by which this temperature is controlled.

A replica of the creep specimen is mounted directly below the creep specimen and has an iron constantan thermocouple resistance welded to it at each end and also at the center. Its function is to monitor the temperature distribution along the specimen. The temperature distribution is constant to within 2^o C at 340^o C with beam off. Since the intensity of the beam may vary along the wire it is necessary to monitor the temperature distribution continuously and perhaps make adjustments in the voltage and position of the cyclotron deflector to produce a more nearly uniform beam distribution. Such adjustments are made whenever the monitor thermocouples indicate that the beam has drifted horizontally. A typical horizontal beam distribution is shown in Fig. 3.

The Al specimen was prepared from 0.0136-inch diameter aluminum wire obtained from Sigmund Cohn Company, New York City and stated by them to be 99.99 per cent pure. Each end is heated with a torch until a ball appears. Tungsten leads are attached by means of a glass bead so that a ball and socket joint is formed. A specimen is shown in Fig. 4. The 0.003-inch iron constantan thermocouple wire is spot welded near the center and the specimen is assembled in the target box. One of the tungsten leads is anchored to the box and the other passes over the extensometer wheel to the weight. The extension is measured by the differential transformer

extensometer shown in Fig. 2. A calibration is made by means of the optical lever described in Ref. 8.

The differential transformer is used in these experiments in both the extensometer and in the conversion of a Foxboro dynalog recorder to a temperature controller. The principle on which it operates is as follows. A coil of fine copper wire is mounted on a light non-magnetic paddle and is attached to the object whose motion is to be measured and recorded. This paddle moves in the air gap between two opposed U-shaped iron transformer cores. The pick-up voltage of the coil is proportional to the distance from the null point and changes phase as the null point is crossed. The sensitivity is 100 microvolts per micro-inch at 400 cycles and several times that at 10 kilocycles. It was developed in the North American Aviation Aerophysics Laboratory for other purposes. A schematic diagram of the extensometer circuit is shown in Fig. 5.

The thermal emf of the specimen thermocouple is recorded on a circular Foxboro dynalog chart driven by an electric clock giving one hour per revolution. The extensometer reading and the emf of the monitor thermocouples is recorded on the strip chart of a 16 point printing potentiometer. A sample of the data is shown on Figs. 6 and 7. It will be noted that the temperature of the replica wire experiences a sharp jump when the beam is "on" relative to the "beam-off" condition. This is due to the specimen and replica being in different radiation fields. The point of significance is the spread of temperatures in the "beam-on" condition relative to the "beam-off" condition. If this spread is excessive the cyclotron adjustments mentioned previously are made.

The specimen is annealed at 330 psi stress at 340° C for 10 minutes. It is then cooled, the weight giving a stress of 892 psi is applied and the temperature at which the creep rate is to be measured is attained. The cyclotron is adjusted so that the temperature distribution along the wire is fairly constant. The specimen is then allowed to creep with radiation at various levels and without radiation, alternately. By this technique the effect of radiation on creep rate can be directly determined on a single sample; no comparison need be made between the creep rates of two different samples. Similar

techniques have been used to study the effects of surface conditions and other variables on creep rate by numerous authors.[9,10,11,12] The sensitivity of the extensometer is such that the creep rate can be measured in an interval as short as 5 minutes. Since this interval is so short, the creep rate during it does not change significantly with time. Typical examples are shown in Fig. 6 where the creep rate with radiation returns to nearly the same value after a period without irradiation. The reverse sequence is exhibited in Fig. 7 where the creep rate increases slightly after a period of irradiation. More details are given in Table I where in many cases it will be seen that the creep rate without irradiation returns to its original value after a period of irradiation.

Since the creep rate is known to be very sensitive to temperature, the detection of a small radiation effect on creep presumes excellent temperature control. Ordinarily this may be accomplished by well known techniques but in the present case the situation is complicated by the fact that the diameter of the specimen wire must be less than the range of the alpha particles (0.021 inch) in aluminum and therefore it has a short thermal time constant. Furthermore, the cyclotron beam supplies a large portion of the heating power and is subject to fluctuations and sudden interruption. This means that there must be a very short response time for the temperature control servo-system. The initial rate of cooling of the creep specimen when the beam is turned off is in the range of 100° C to 300° C per second. The rate of cooling of the specimen will be higher at the higher beam intensities since the tubular heater then operates at a lower temperature. The writing speed of the dynalog is about 50° C per second. The slowest response of all is the tubular heater which cools initially at 15° C per second. A block diagram of the temperature controller is given in Fig. 8.

Another difficulty to be considered is the modulation of the beam due to multiples of the power frequency and to frequencies originating in the arc. Studies of the beam using a Tektronix oscilloscope Model 512 show that 30 per cent to 100 per cent modulation of the beam exists. We have measured a temperature fluctuation due to this cause of $\pm 5^{\circ}$ C. The effect of rapid temperature cycling on creep rate is not known. However, inspection of Fig. 9 will show that the relation between temperature and creep rate is linear over small ranges of temperature within the accuracy needed in this experiment. We have

therefore tentatively assumed that experiments may be discussed in terms of the average temperature. (The above remark applies for the same reason to the effect of small temperature deviations along the wire.) There are some reservations however, and this point is discussed more fully in Part IV.

Improvements in the temperature control and in the steadiness of the beam can be made, but it was felt that in spite of the temperature cycling and the slow response of the temperature control system much valuable information might be obtained. As the data exhibited in Figs. 6 and 7 show, the cyclotron beam was often steady enough so that the temperature controller maintained a temperature within satisfactory limits for periods sufficiently long to obtain reliable results.

A further possible means by which a spurious result might be obtained is in the effect of the beam on the thermocouple. This was looked for experimentally in the following way. An iron-constantan couple was spot welded to an aluminum wire. The thermal emf was amplified by a DC amplifier (Tektronix Model 512) and fed to the DC amplifier of an oscilloscope. The system passed frequencies from DC to two megacycles. The wire was heated by the beam and the oscilloscope trace shown in Fig. 10A and B obtained. The beam was turned off by several methods; namely, opening the main breaker to the oscillator, turning off the arc, turning off the deflector, and closing the target gate. In each case a trace similar to that in Fig. 10A and B was obtained A similar trace in which the input to the oscilloscope was the voltage due to the beam current through a resistance is given in Fig. 10C and D. The two are shown superimposed on the same time scale in Fig. 10A. If a radiation emf existed it might be expected to disappear at a rate different from the temperature decay rate of the wire. The trace on Fig. 10A and B shows only the normal fall of temperature due to cooling. We conclude that the thermocouple emf is a reliable measure of temperature under the conditions of the experiment. The highest beam intensity at which this experiment has been done is 8 microamperes.

III. DATA AND RESULTS

A. Creep

The data obtained during a typical run appear in Fig. 7, where the creep

strain in the specimen, its temperature, and the temperature distribution along the replica wire are plotted against time. The specimen temperature appears on the circular chart. During the interval from 0 to 12 minutes, the beam was off; during the interval from 12 to 18.5 minutes the beam was on, but the beam current was erratic, as is evident from its temperature record. From 18.5 to 24 minutes steady beam conditions prevailed, with a beam current of 3 microamperes. At 24 minutes the beam current was shut off. The suppression of creep rate produced by the beam current is apparent from the reduced slope of the strain-time curve during the time the beam current was on; during this interval, the specimen temperature fluctuated somewhat in time but its average value was maintained the same as when the beam was off. The temperature distribution along the specimen wire during this interval can be deduced from the distribution along the replica wire.

The data appearing in Fig. 11 where the ratio of creep rate at various values of beam current to the creep rate at zero current is plotted against beam current, were obtained from a succession of such observations of creep rate as a function of beam current. Since the creep rate is sensitive to temperature, and the temperature distribution along the wire does not remain the same when the beam is turned on, it is important to compare the change in the average temperature along the specimen when the beam is turned on with the change in temperature which would be required to decrease the creep rate by the amount observed. Such a comparison can be made with the data appearing in columns five and eleven of Table I. It is apparent that the change in average temperature is in all cases much less than the temperature change required to suppress the creep rate by the amount observed.

There are, then two criteria to be applied to the data as exhibited in Table I to indicate the presence of a radiation effect on creep. First, the creep rate with irradiation must be compared with a preceding or following measurement without irradiation. Second, the average temperature change of the wire must be insufficient to account for the observed change in the creep rate with beam on.

Numerous examples will be found in Table I where it must be concluded that the creep rate is suppressed by the presence of the alpha particle beam.

The data are given in graphical form in Fig. 12 where considerable scatter will be observed. This is due to several factors, among which the variable beam shape is believed to be the principal one. The beam which passes through the first collimating slot is the quantity specified in each case. Measurements of numerous beam shapes indicate that the intensity at the sample may vary by $\pm$ 20 per cent at various times for a given total beam. It will be noted however, that in each case there is a reduction of the creep rate in the presence of irradiation.

B. Possible "Expansion" Effect

At an earlier stage of these experiments, it was intended to use the extensometer as a thermometer and to locate the creep specimen just above the point of maximum beam intensity and a control replica at a point of equal intensity just below. It was hoped that agreement between the temperature given by the thermocouple on the replica and by the specimen extension would provide a proof that the specimen temperature was properly measured in the radiation field. A further advantage of this method was thought to be that it avoided the necessity of welding a thermocouple to the creep wire.

Difficulty was encountered in carrying out the above procedure and so a creep specimen with a thermocouple attached was tried. It was seen in this experiment that the effect which was thought to be due to a misadjustment of the creep specimen with respect to the beam was due to some other cause.

The effect is shown in Figs. 6 and 7 as inspection of the extensometer record at those times when the beam was turned on or off will reveal. In Fig. 7 at 24 minutes, when the beam is turned off, there is a sudden decrease in the total length of the specimen plus attached lead wires. At 25 minutes, when the temperature indicated by the thermocouple is again constant after a transient decays, the total length of specimen and attached leads is shorter by 0.8×10^{-3} inches. The change in average temperature along the wire from "beam-on" to "beam-off" conditions is smaller by a factor of nearly 20 than that required to produce the observed contraction purely as a consequence of the thermal coefficient of expansion of the specimen alone. The effect is reversible within the accuracy of the experiments.

There is a possibility that the effect may be due to a coupling between

the extensometer pick up coil and the heater power circuit. This was checked by clamping the wheel; no "pick up" effect was found when the beam was turned on or off.

It is concluded that the length of the specimen plus leads actually changes between "beam-on" and "beam-off" conditions. There is a contraction of the specimen leads which should be expected due to the fact that when the beam is on and is heating the specimen, the temperature controller allows the heater to cool, thus cooling the support leads. A possible source of the expansion may be that, when the beam is on, the thermocouple leads drain heat from the specimen which would cause the specimen as a whole to increase its temperature because of the action of the temperature regulator.

We have attempted to correct for the first effect in a later experiment by measuring the total extension as a function of heater temperature. The thermal expansion due to the leads can be obtained by subtracting the known expansion of the specimen. These data combined with the heater temperature as a function of the beam intensity can be used to correct the total expansion. This method does not account for heat passing through the glass leads to the specimen leads. It is possible that this is the cause of part of the observed expansion effect.

The results of removing the specimen lead expansion by the above method is shown in Fig. 13. If even a small portion of this extension is due to temperature increase in the specimen related to heat drain down the thermocouple leads the creep effect has been very much underestimated. Further work will be directed toward clearing up these points.

V. DISCUSSION

It is felt by us that the evidence presented here definitely corelates the suppression of the creep rate with the presence of the alpha particle beam. It may be presumed that this effect is due to a primary property of the beam such as ionization or the production of vacancies and dislocations. The possibility exists however, that an effect noted by W. A. Wood[13] and by R. P. Heidenreich and W, Shockley[14] may apply. The temperature oscillation with multiples of the power line frequency mentioned above may cause a stress oscillation due to

thermal expansion and the inertia of the pulley and weight. The effect found by the above authors is that stress cycling causes hardening. The cycling frequency used by W. A. Wood was approximately that which occurs in these experiments. The treatment of the specimen was very much more severe in Wood's experiment than in ours and so it is felt that the possibility that our effect is due to stress cycling is remote. It is planned, nevertheless, to explore this point experimentally.

Because of the sensitive dependence of creep rate on temperature, it was thought important to attempt to have two independent measurements of the specimen temperature; namely, its length and the emf of a thermocouple attached to it. The conditions of the experiment are such that it is not possible to expose the specimen to the beam at constant temperature without at the same time changing other experimental conditions, namely, the power through the heater and the temperature distribution along the specimen leads. The quantities measured are the emf of the thermocouple attached to the specimen and the specimen length, as functions of time and hence beam intensity.

If the observed expansion effect shown in Fig. 13 is all due to an increase in temperature caused by heat drain along the thermocouple wires and the action of the temperature regulator; then, the true suppression of the creep rate is nearly a factor of four more than that shown in Fig. 11. Thus, although the scatter in the data is large, the errors are in a direction such that the suppression of creep effect would be accentuated if they were eliminated or minimized.

The data are interpreted as showing that:

1. The emf of the thermocouple properly indicates its average temperature, and that this is maintained constant under the conditions of the experiment.
2. The creep rate decreases when the beam strikes the sample. For the aluminum wire studied, at 338^{O} C under a stress of 890 psi, the creep rate decreases with beam current as shown in Fig. 11.

EXPLANATION OF DATA TABLE

The data from two cyclotron creep tests have been tabulated in Table I. Column 1 gives the beam current in microamperes through a collimating slot 0.25 inches high and 0.60 inches long. Columns 3 and 4 show the deviation from a flat temperature distribution due to uneven heating by the beam. Column 5 gives the average error in specimen temperature with the beam "on" assuming that the center of the specimen is maintained at a constant temperature which would be required to give the suppression in creep rate observed during bombardment. This dependence of creep rate on temperature was obtained from the data of Fig. 6. If the variation of creep rate with temperature reported by Dushman[15] for aluminum is used, the values in column 11 should be approximately divided by 2.

TABLE I

Beam μa	Temperature of Speciment	Temp. Distribution Difference from Center monitor in C^o Inside	Outside	Average	Time From Start of Run Minutes	Duration of Individual Tests	Creep Rate Sec^{-1}	Ratio B*	Ratio A*	Temp. Chg. Req. to Give Suppression
November	29 Run									
0	328 ± 0.3				50	15	2.9×10^{-6}			
2.2	328 ± 3.0	-2	-14	-4	66	5	1.3	0.46	0.43	-20
0.9	328 ± 0.5	-2	- 3	-2	75	6	1.2	0.41	0.39	-21
0	328 ± 0.3				90	15	3.1			
0	328 ± 0.3				108	6	4.9			
1	329 ± 2	+3	- 4	0	113	4	3.1	0.64	0.96	- 3.5
2	328 ± 2	0	- 5	-2	118	5	2.2	0.45	0.68	-16
0	328 ± 0.3				128	6	3.2			
1	328 ± 2	0	- 2	-0.5	133	5	2.4	0.73	0.63	-10.5
2	328 ± 1				138	2				
0	329				150	13	3.7			
1	326				156	2				
0	329				158	3	3.7			
1	329 ± 0.5	-3	0	-1	163	4	1.3	0.36	0.34	-23
2	329 ± 0.5	-3	0	-1	170	7	2.5	0.65	0.62	-11
0	329 ± 0.2				180	8	3.9			
2	326 ± 3				187	3	2.2	0.57		-16
2.3	329 ± 2	-4	+ 1	-1	192	4	1.5	0.38		-21

Stress 900 psi

Cyclotron creep test 29 November 1950. Temperature controlled with 0.003 inch iron-constantan thermocouple welded to 0.0136 inch aluminum specimen of 0.500 inch gauge length. Stress at start of test 900 psi.

TABLE I Continued

Beam μa	Temperature of Specimen	Temp. Distribution Difference from Center monitor in C^o			Time From Start of Run Minutes	Duration of Individual Tests	Creep Rate Sec^{-1}	Ratio B*	Ratio A*	Temp. Chg. Req. to Give Suppression
		Inside	Outside	Average						
										Stress 900 psi
1	358 ± 2	-3	2	0	233	5	13.3×10^{-6}		0.94	- 1
0	358 ± 0.5				237	5	14.3			
2	358 ± 3	-2	4	-1	243	5	11.1	0.83	0.72	- 7.5
0	358 ± 1				245	3	15.6			
0	338 ± 0.2				250	13	6.8			
3.5 ± 0.5	338 ± 4	-7	0	-2	255	8	2.7	0.38	0.35	-23
3.0 stdy.	338 ± 2	-2	-4	-1.5	260	5	5.2	0.74	0.68	- 9.5
0	338 ± 0.3				270	10	7.6			
3	338 ± 3				277	3	1.6	0.21	0.21	-30
3 stdy.	338 ± 3	-5	-2	-2	279	3	4.7	0.62	0.62	-13
1.4	338 ± 2	+3	-4	0	282	2	7.0	0.92	0.92	- 1
0	332				283	1/2	7.6			
1.9	338 ± 1	-2	0	-1	300	6	6.3	0.83	0.83	- 4
0	338 ± 0.3				305	5	7.6			
1.2	338 ± 1	+2	-2	0	313	5	6.9	0.91		- 2
0.5	338 ± 0.5	+1	-1	0	318	5	6.9	0.91		- 2
0.25	338 ± 0.5	+1	-1	0	325	7	6.9	0.91		- 2
0.12	338 ± 0.5	+1	-1	0	329	4	6.9	0.91		- 2
0.05	338 ± 0.5	0	0	0	333	3	7.6	1.00		
0					337	3	8.0	1.06		

TABLE I Continued

Beam μa	Temperature of Specimen	Temp. Distribution Difference from Center monitor in C^o Inside	Outside	Average	Time From Start of Run Minutes	Duration of Individual Tests	Creep Rate Sec^{-1}	Ratio B*	Ratio A*	Temp. Chg. Req. to Give Suppression	
Defl. & OSC off											Stress 900 psi
1.6	339 ± 3	0	-8	-2	360	5	5.4	0.71		- 9.5	
0	291 ± 0.3				370	5	9.3 x 10^{-6}				Stress 1200 psi
2.4	291 ± 2	-7	-1	-4	380	5	5.5	0.62	0.82	- 9.5	
1.2	291 ± 1	-1	0	0	387	4	6.2	0.70	0.92	- 6	
0.6	291 ± 1	0	0	0	390	3	6.2	0.70	0.92	- 6	
0.2	291 ± 1	0	0	0	392	2	6.2	0.70	0.92	- 6	
0.1	291 ± 1	0	0	0	395	5	7.1	0.80	1.05	- 2	
0.05	291 ± 1	0	0	0	400	2	7.1	0.80			
0	291 ± 1	0	0	0	403	3	6.8				
1.45	291 ± 1	-3	0	-1	410	6	6.0	0.88	0.74	- 6	
0	291 ± 0.3				417	7	8.0				
Cyclotron Creep Test 23 November 1950											Stress 900 psi
3.0 ± 0.4	338 ± 1.5	-3	-2	-2.5	0	7	7.1 x 10^{-6}		0.73	- 8	
0	338 ± 0.5	0	0	0	15	5	10.2				
3.6 ± 0.6	338 ± 2.0	+2	+1		20	7	6.4	0.63	0.73	-10	
0	338 ± 0.5	0	0	0	30	8	8.9				
0	338 ± 0.5	0	0	00	37	5	10.2				
3.7	338 ± 1.0	-7	-3	-5	50	12	6.2	0.61		-13	

*Ratio A is the ratio of creep rate with beam to creep rate without beam where the no beam measurement preceeds the measurement made with beam. Ratio B uses the no beam measurement following the beam measurement.

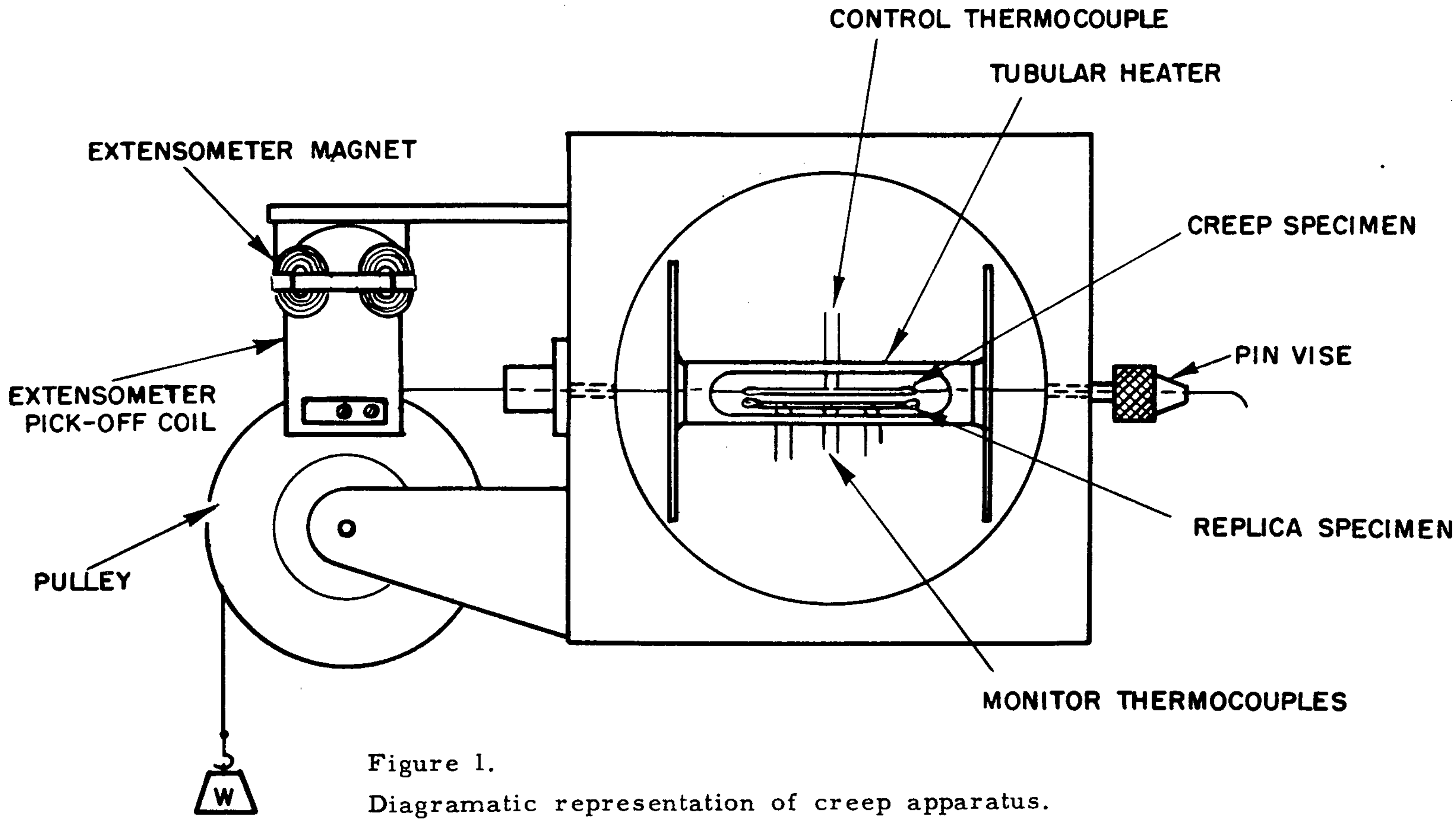


Figure 1.
Diagramatic representation of creep apparatus. Specimen and replica are irradiated by the beam passing through slots in the tubular heater. Beam direction is into the paper.

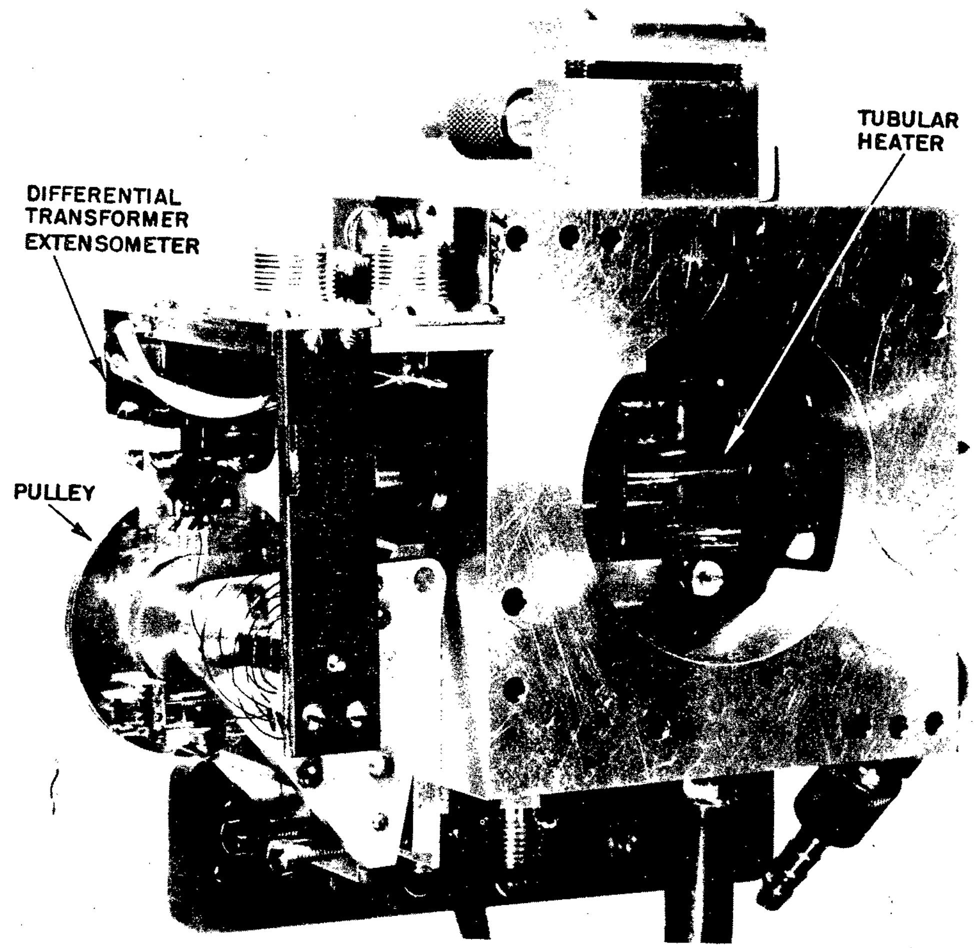


Figure 2.

Photograph of creep target box showing tubular heater with beam slot. A collimating slot and aluminum window attach to the face of the box. A tungsten wire for applying stress to the creep specimen passes over the pulley on the left and terminates in a hook for attaching weights. The collimating mirror (not visible) is mounted in the pulley shaft.

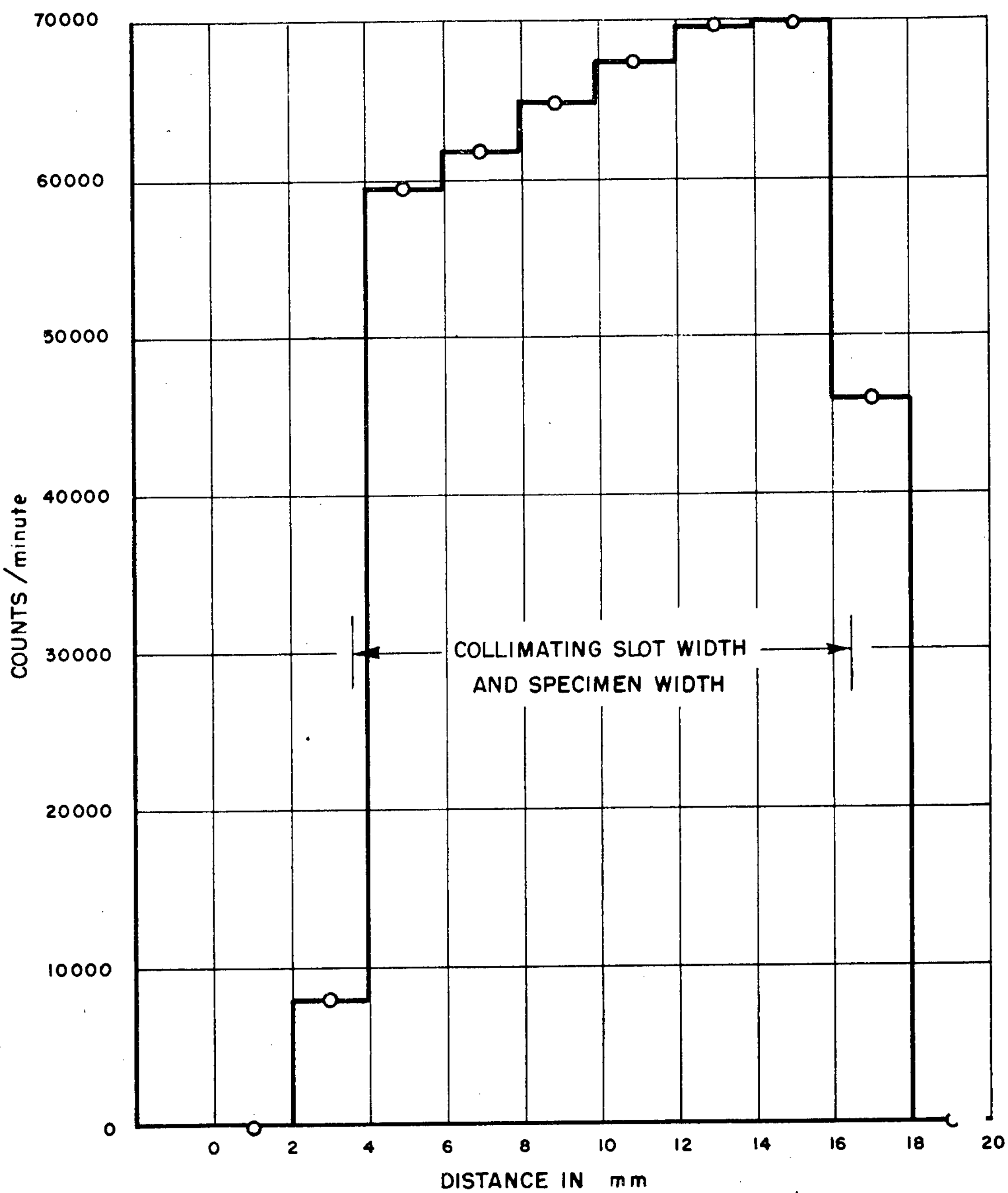


Figure 3. Typical Horizontal Beam Distribution Obtained by Counting Beta Activity of a Copper Wire Placed Alongside the Creep Specimen.

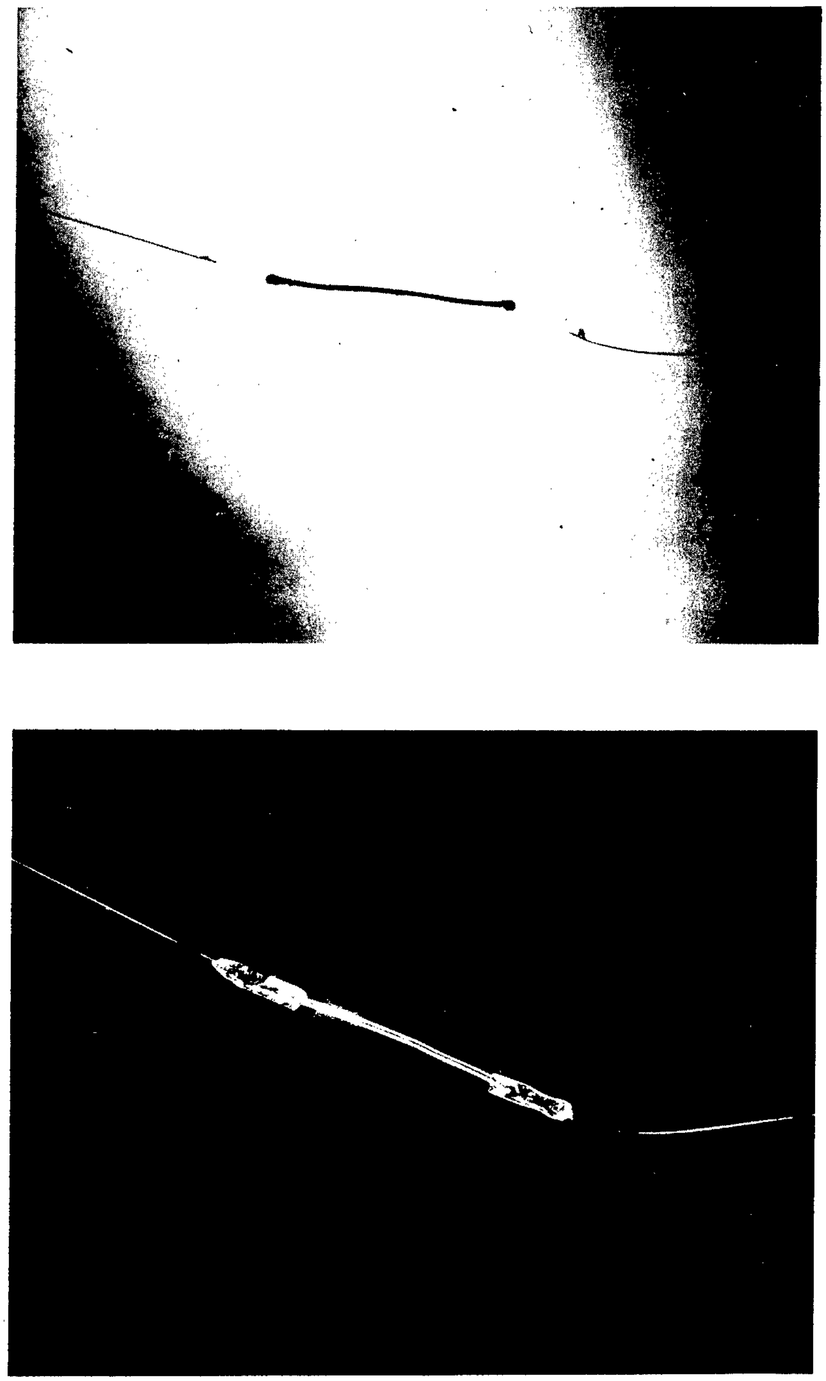


Figure 4. Creep Specimen Showing Method of Attaching Leads.

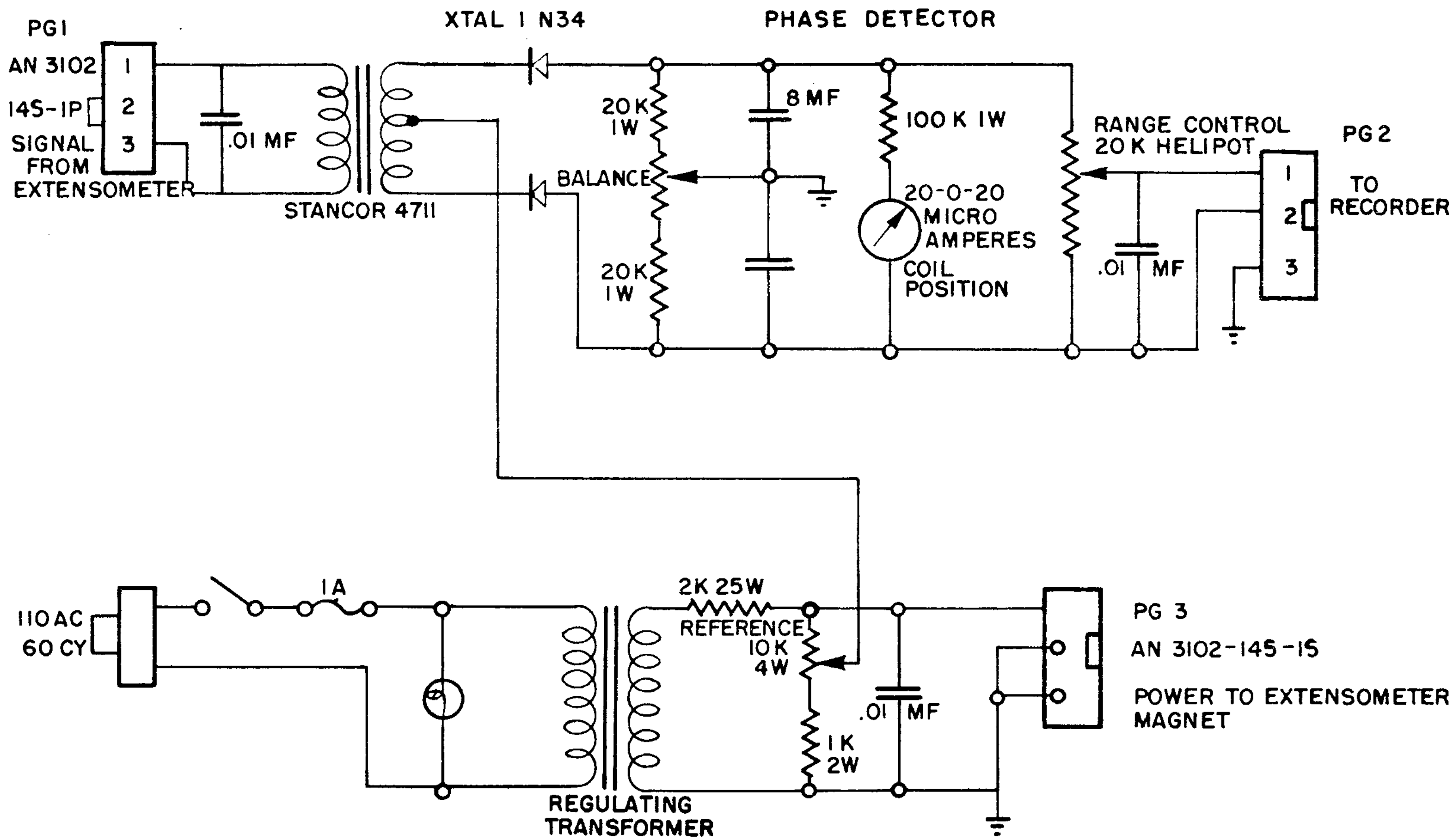


Figure 5. Extensometer Schematic. All Resistors Precision Wire Wound.

Figure 6.
CREEP OF ALUMINUM AS A FUNCTION OF BEAM AND AT CONSTANT TEMPERATURE. "RADIATION EXPANSION" IS RECORDED AT VARIOUS BEAM LEVELS. REVERSIBILITY OF STRUCTURE IS ILLUSTRATED AT 26 MINUTES ON THE TIME SCALE WHERE THE BEAM WENT OFF MOMENTARILY.

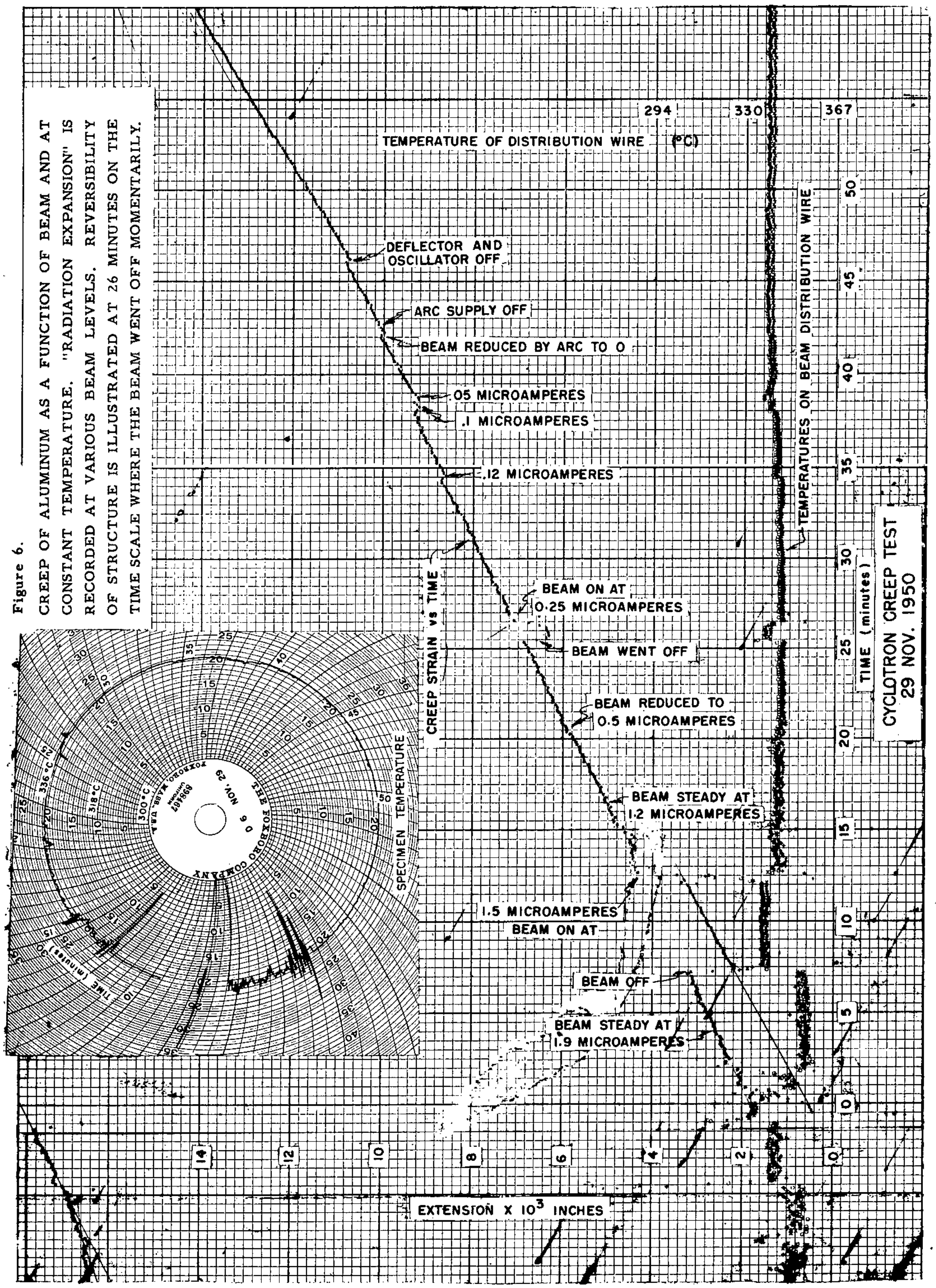
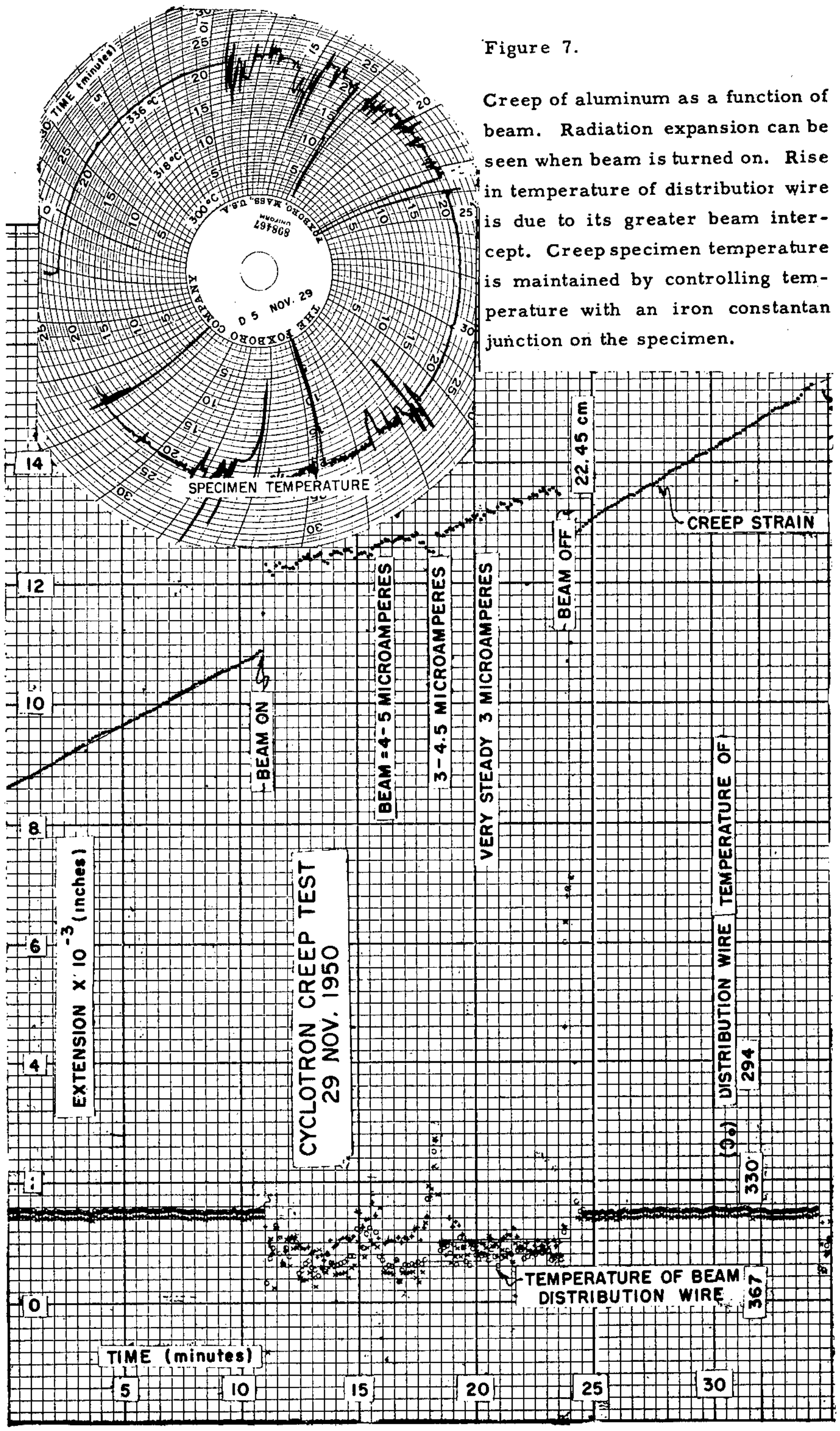


Figure 7.

Creep of aluminum as a function of beam. Radiation expansion can be seen when beam is turned on. Rise in temperature of distributior wire is due to its greater beam intercept. Creep specimen temperature is maintained by controlling temperature with an iron constantan junction on the specimen.



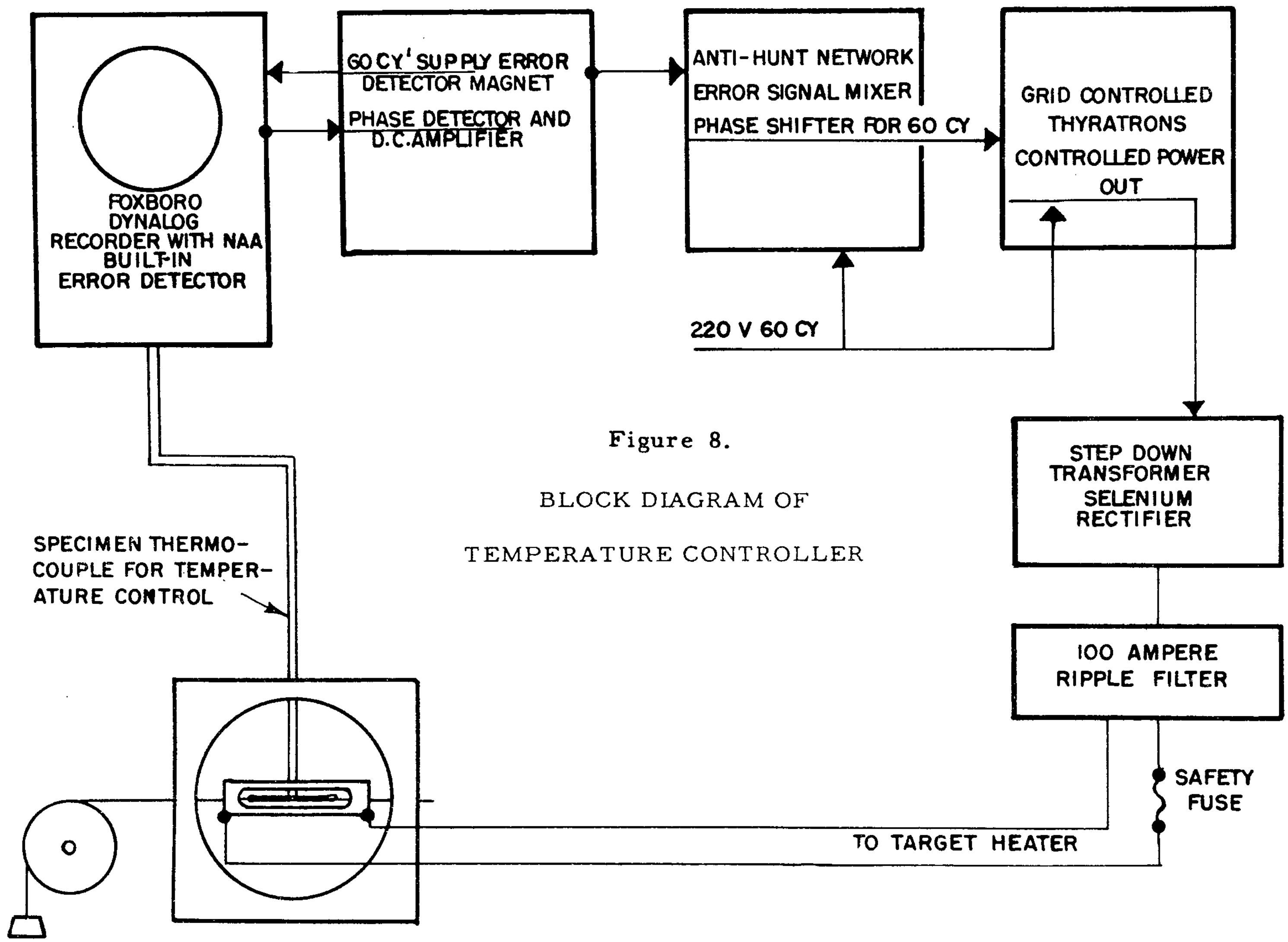


Figure 8.

BLOCK DIAGRAM OF

TEMPERATURE CONTROLLER

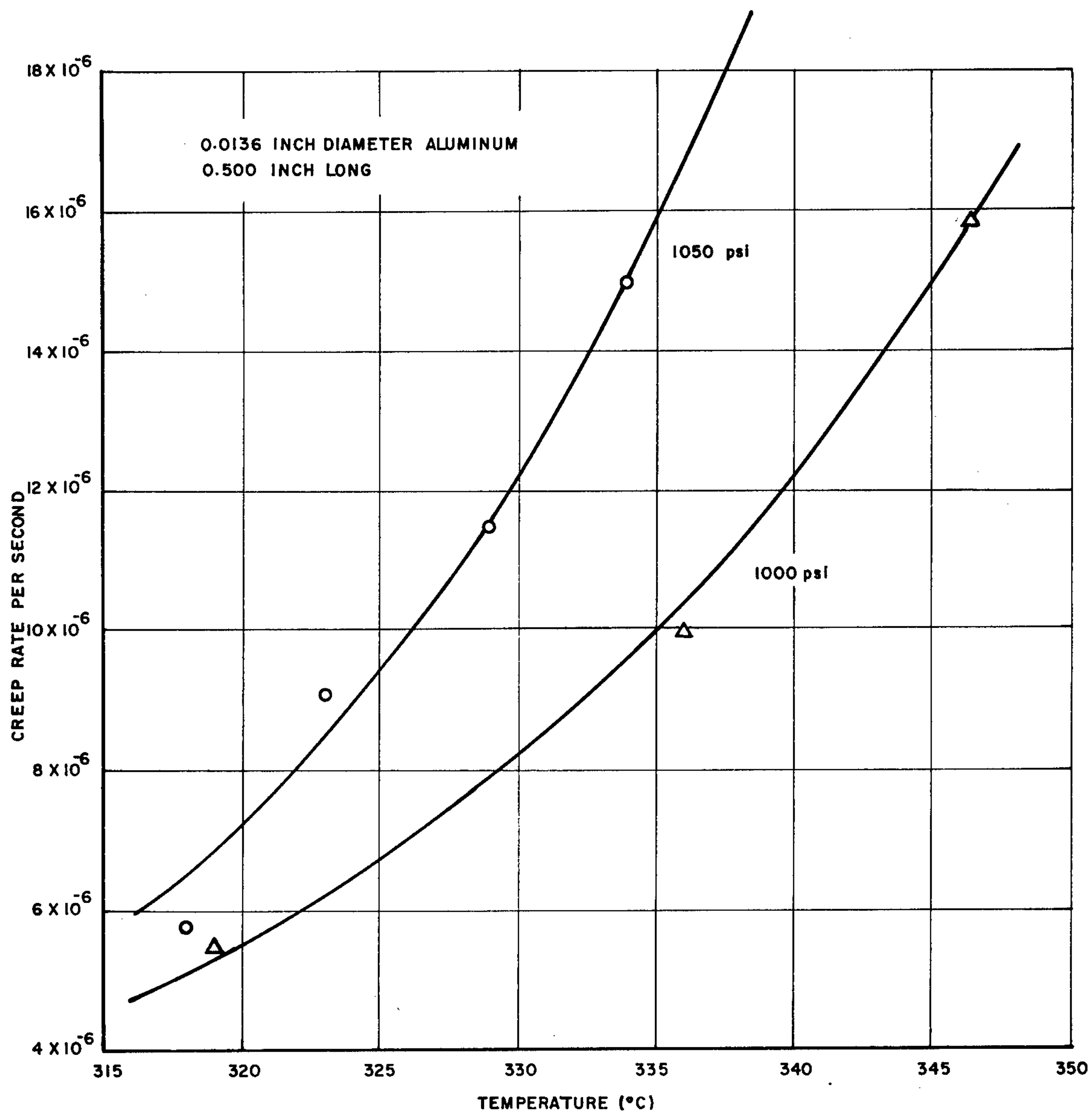
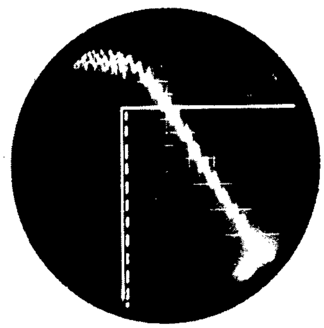


Figure 9. Creep Rate vs Temperature.

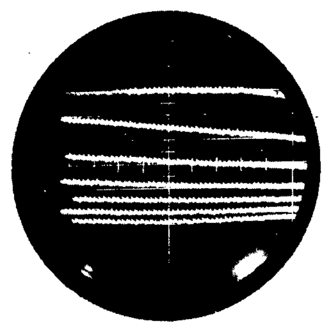
Photograph of iron constantan thermocouple emf showing temperature decay from 350° C when 7 microampere alpha beam is turned off by cyclotron RF oscillator. Horizontal calibration 0.1 second/cm, vertical calibration 0.5 millivolt/cm. Actual beam decay from photograph C is superimposed using the same time scale as the thermocouple emf. This shows that the beam goes off about 60 times faster than the temperature decay.



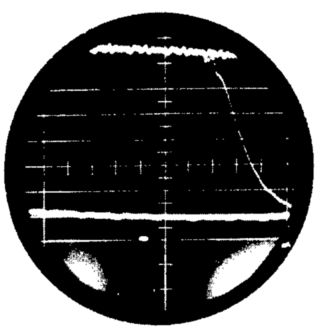
A

Temperature decay of aluminum creep specimen when 5 microampere deuteron beam is turned off with RF oscillator. Initial temperature 170° C.

Horizontal calibration 0.1 second/cm, vertical 1 millivolt/cm.



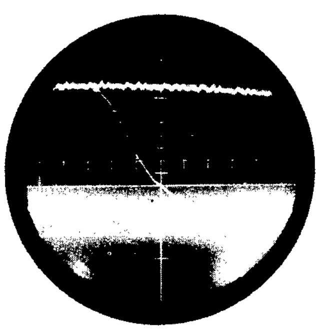
B



C

Decay of 1 microampere alpha beam when oscillator is turned off.

Horizontal calibration 12 milliseconds per cm.



D

Decay of 1 microampere alpha beam when arc is turned off. Horizontal calibration 12 milliseconds per cm.

Figure 10.

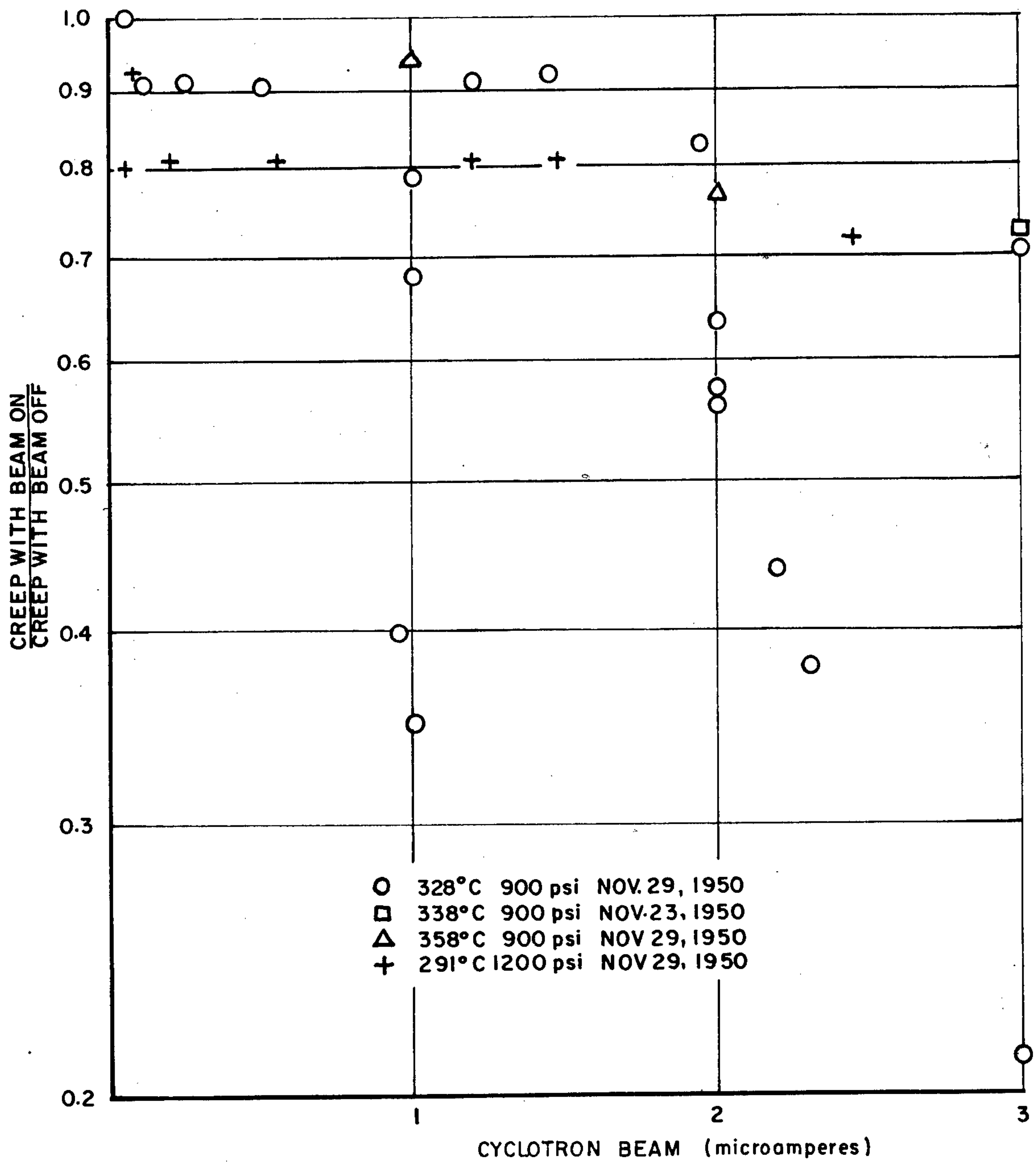


Figure 11. Supression of Creep in Aluminum with Presence of Cyclotron Alpha Particle Beam.

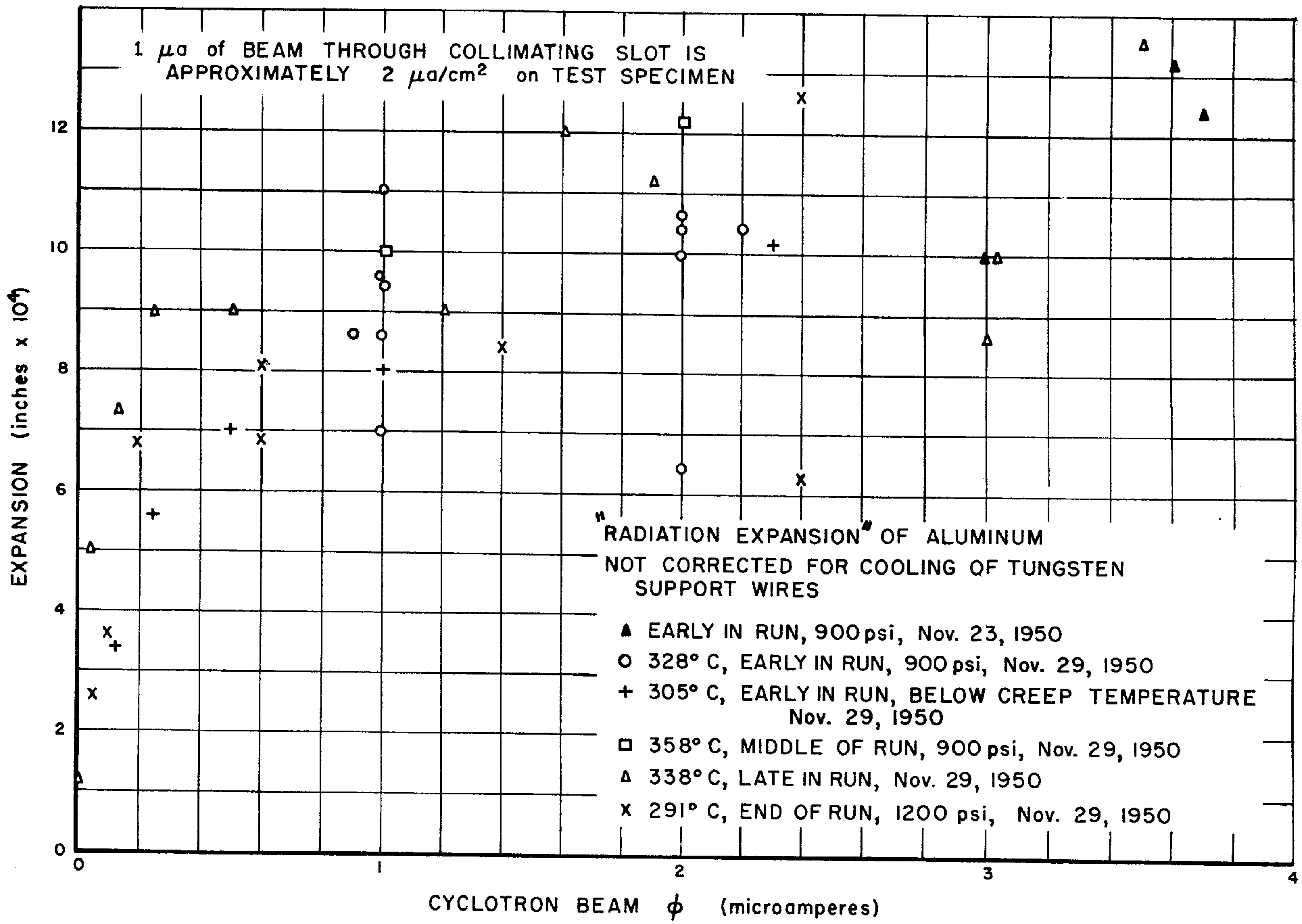


Figure 12. "Radiation Expansion" of Aluminum.

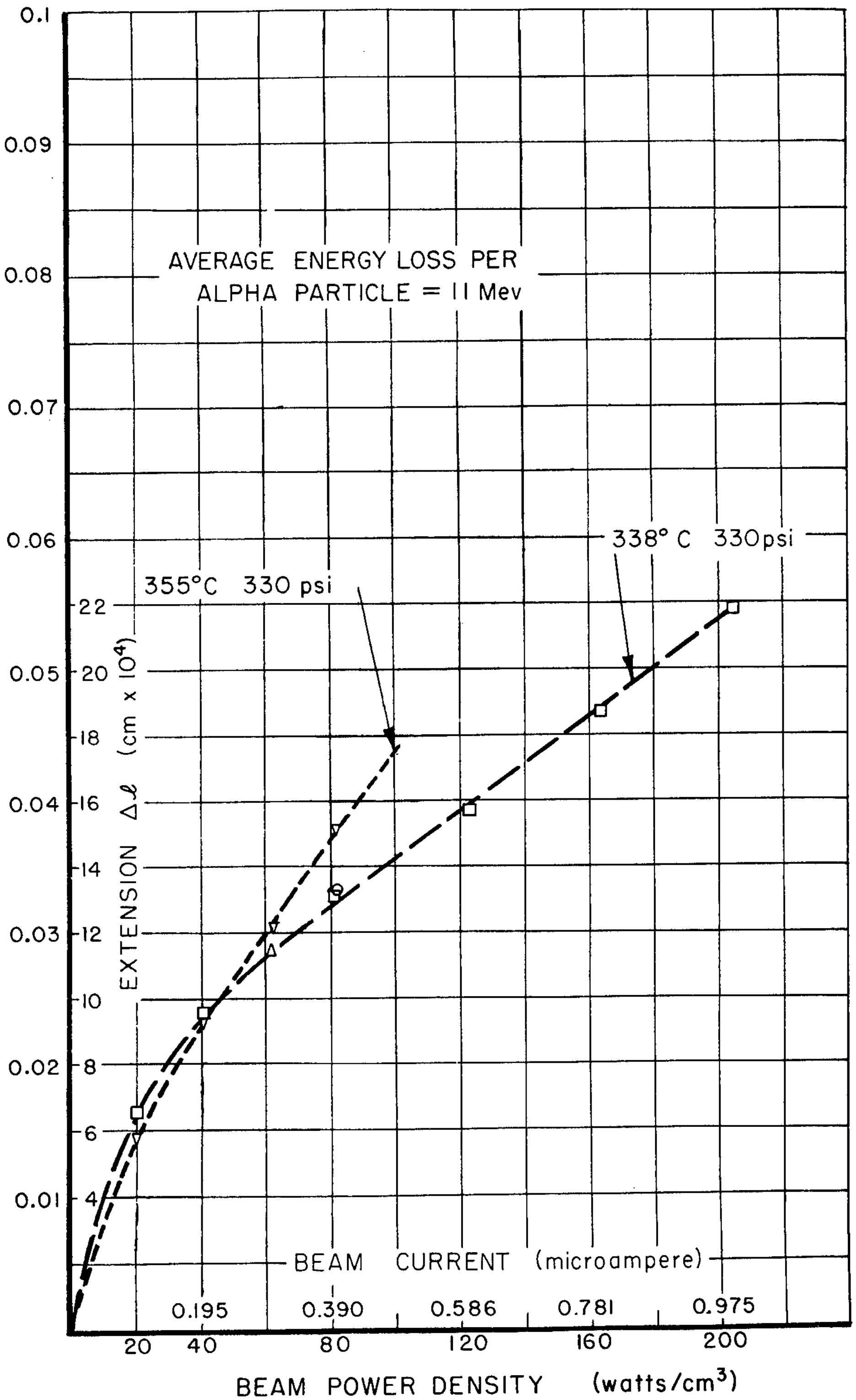

0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
22
20
18
16
14
12
10
8
6
4
EXTENSION $\Delta \ell$ (cm x 10^4)
AVERAGE ENERGY LOSS PER
ALPHA PARTICLE = 11 Mev
355°C 330 psi
338° C 330psi
BEAM CURRENT (microampere)
0.195
0.390
0.586
0.781
0.975
20
40
80
120
160
200
BEAM POWER DENSITY (watts/cm^3)

FIG. 13

REFERENCES

1. Dienes, G. J., "A Program for the Study of Radiation Effects on Mechanical Properties", NAA-SR-71, June 7, 1950.

2. Slater, J. C., et al., "Survey of Effects of Radiation on Materials", AEC-500, 1949.

3. Andrade, E. N., da C., "Effects of Alpha-Ray Bombardment on Glide in Metal Single Crystals", Nature (1945) 156.

4. Kittel, J. H., "Preliminary Effects of Alpha Particle Bombardment on the Creep Rate of Aluminum", NACA RM No. E7E13, July 3, 1947.

5. Martin, A. B., and M. M. Mills, "The Application of Particle Accelerators to the Study of Radiation Damage", NAA-SR-56, July 24, 1950.

6. Faris, F., "Results of Resistivity-Range Measurements on Graphite Bombarded with Charged Particles", NAA-SR-14, October 12, 1950.

7. Yockey, H. P., "Cyclotron Techniques and Studies of Radiation Effects", NAA-SR-21, December 22, 1948.

8. Malmstrom, C. R., and R. Jewell, "A Creep of Metals Apparatus for Use with the Berkeley Cyclotron", NAA-SR-49, December 21, 1949.

9. Philips, D. J., and N. Thompson, "Surface Effects in Creep of Cadmium Crystals", Proc. Phys. Soc. 63 839 (1950).

10. Davis, M., and N. Thompson, "Creep in a Precipitation Hardened Alloy", Proc. Phys. Soc. 63, 847 (1950).

11. Harper, S., and A. H. Cottrell, "Surface Effects and the Plasticity of Zinc Crystals", Proc. Phys. Soc. 63, 331 (1950).

12. Wain, H. L., and A. H. Cottrell; "Yield Points in Fine Crystals", Proc. Phys. Soc. 63, 339 (1950).

13. Wood, W. A., "Crystaline Structure and Deformation of Metals", Proc. Phys. Soc. 52 (1940) 110.

14. Heidenreich, R. D., and W. Shockley "Study of Slip in Aluminum Crystals by Electron Microscope and Electron Diffraction Methods", Report of 1947 Bristol Conference on Strength of Solids; Physical Society (London), 1948.

15. Dushman, S., L. W. Dunbar, and H. Huthsteiner, "Creep of Metals", Journal of Applied Physics 15 (1944), pp 108-124.